Effects of dielectric material and linewidth on thermal stresses of Cu line structures

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Objectives

- Determine thermal stresses in Cu lines in Cu/low-k damascene structures under thermal cycling using x-ray diffraction method

- Use Finite Element Analysis (FEA) to evaluate thermal stresses and deformation behavior of ILD

Dielectrics: SiOF, SiLK™ and CDO
Linewidth: 0.4 µm, 0.2 µm

Outline

- X-ray diffraction method for measuring thermal stresses
- The schematic of test structures
- Characteristics of thermal stresses in Cu lines
- 3D finite element analysis (FEA)
- Summary

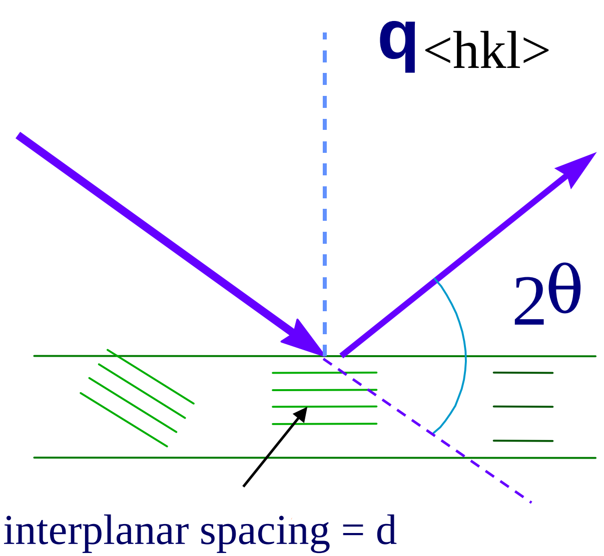
X-ray diffraction method for measuring stress

Strain determination

Bragg's law : $\lambda = 2d \sin\theta$

For a cubic crystal system:

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$



$\theta \rightarrow d_{hkl} \rightarrow a \rightarrow$ Strain in q <hkl> direction: $\varepsilon = (a - a_o) / a_o$

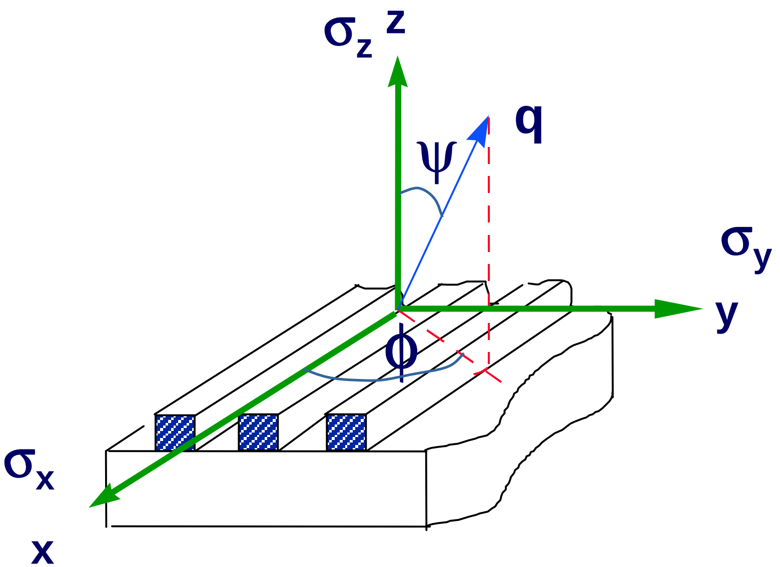
λ : X-ray wavelength

a_o : Unstressed lattice parameter

X-ray diffraction method for measuring stress

Sample geometry

$$\varepsilon_{\phi\psi} = \varepsilon_{xx}\cos^2\phi\sin^2\psi + \varepsilon_{xy}\sin 2\phi\sin^2\psi + \varepsilon_{yy}\sin^2\phi\sin^2\psi + \varepsilon_{zz}\cos^2\psi + \varepsilon_{xz}\cos\phi\sin 2\psi + \varepsilon_{yz}\sin\phi\sin 2\psi$$



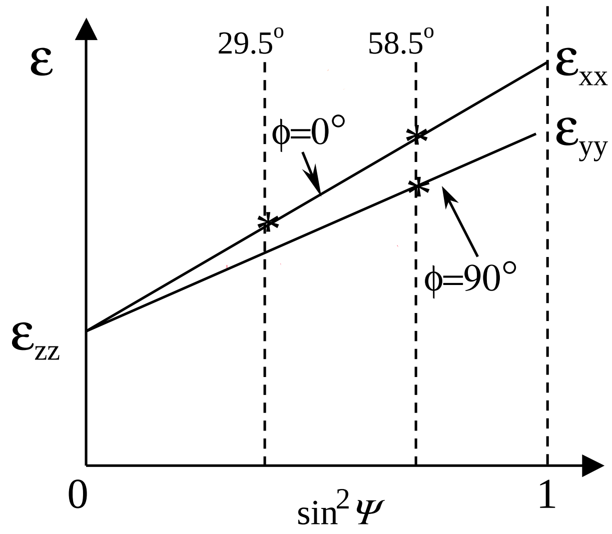
Omit the shear components:

$$\varepsilon_\psi = (\varepsilon_{xx}-\varepsilon_{zz})\sin^2\psi + \varepsilon_{zz} \quad \text{at } \phi=0^o$$

$$\varepsilon_\psi = (\varepsilon_{yy}-\varepsilon_{zz})\sin^2\psi + \varepsilon_{zz} \quad \text{at } \phi=90^o$$

(311) plane spacing was measured at different inclination angles. At $\phi=0^o$, $\psi=29.5^o$, 58.5^o. At $\phi=90^o$, $\psi=58.5^o$. $\rightarrow \varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}$, then

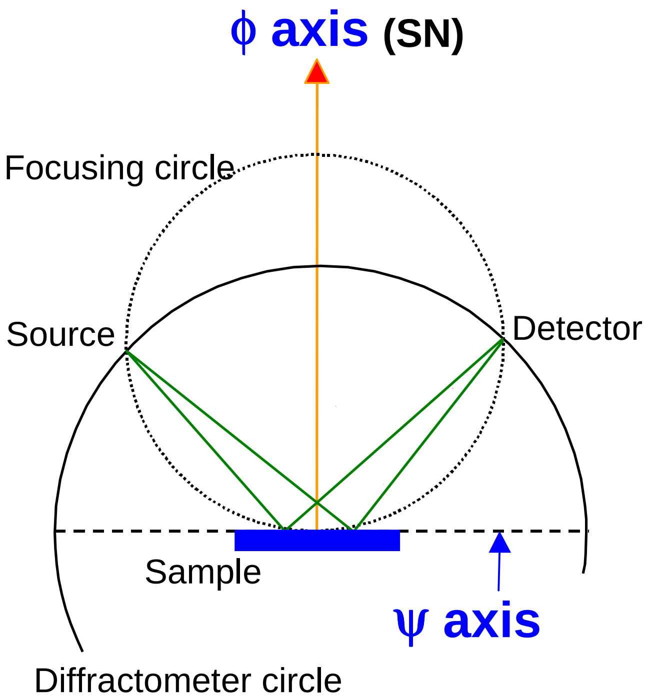
$$[\sigma] = [C][\varepsilon]$$



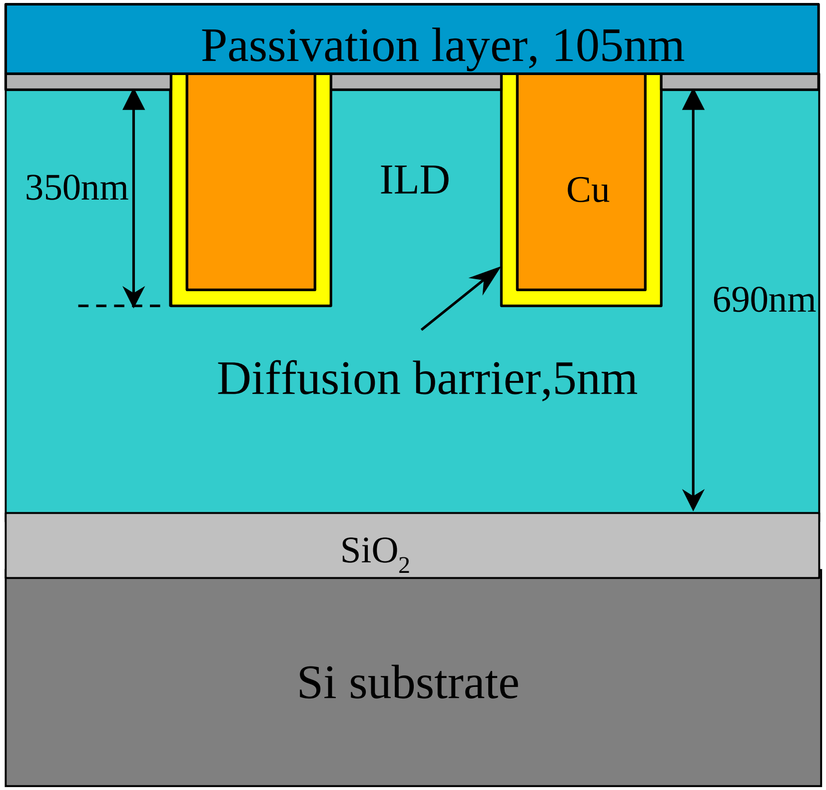
X-ray diffraction method for stress measurement

System geometry

- Four circle diffractometer
  (θ, 2θ, ψ, ϕ)
- High intensity x-ray source
- In-situ heating stage



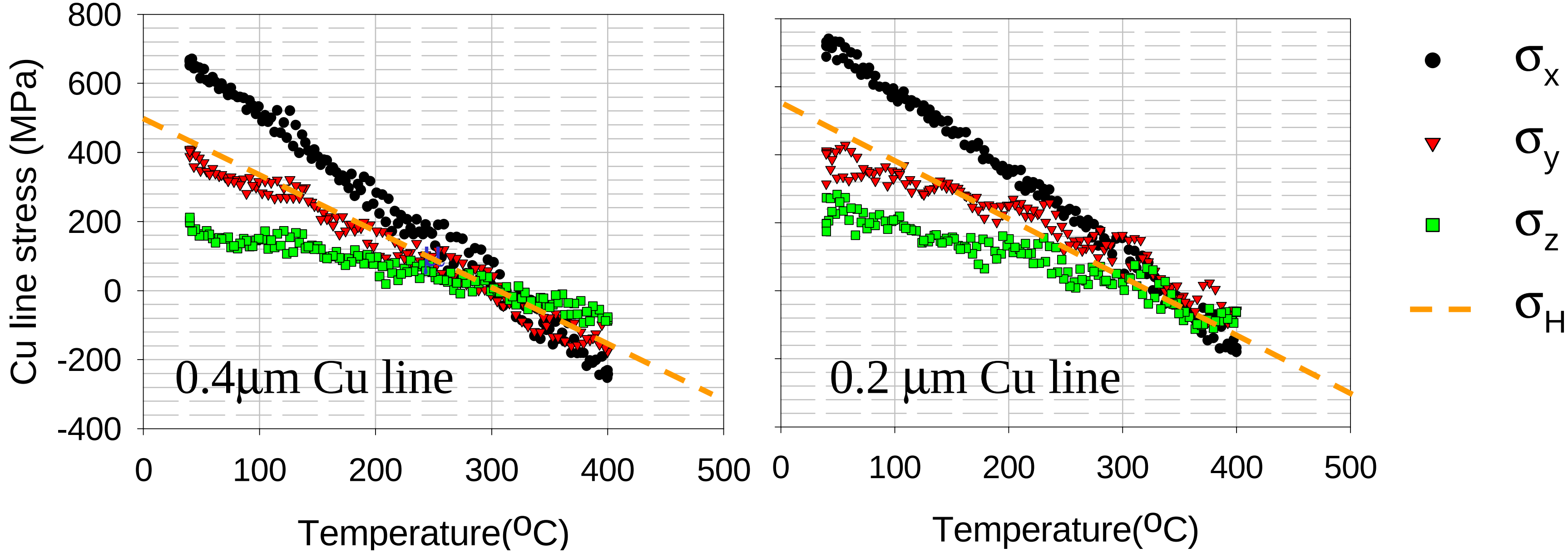
Schematic of test structures



- Two sets of line width/pitch: 0.4/0.4 μm and 0.2/0.2 μm
- Three types of ILD: SiOF, SiLK™ and CDO

Characteristics of thermal stress of Cu lines

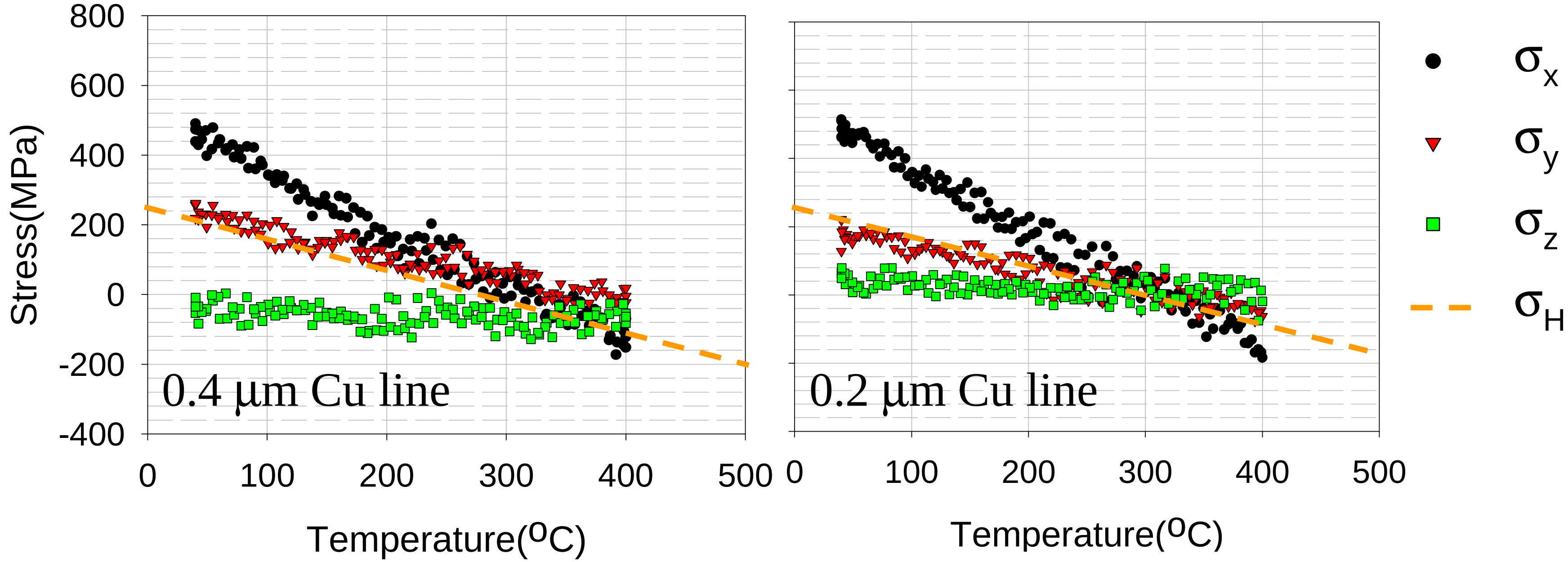
1. Stresses in Cu lines (Cu/SiOF damascene structure)



- Linear behavior with temperature
- Tensile at room temperature, compressive at 400^{o}C
- σ_H --Driving force for void formation, only weakly dependent on linewidth

Characteristics of thermal stress of Cu lines

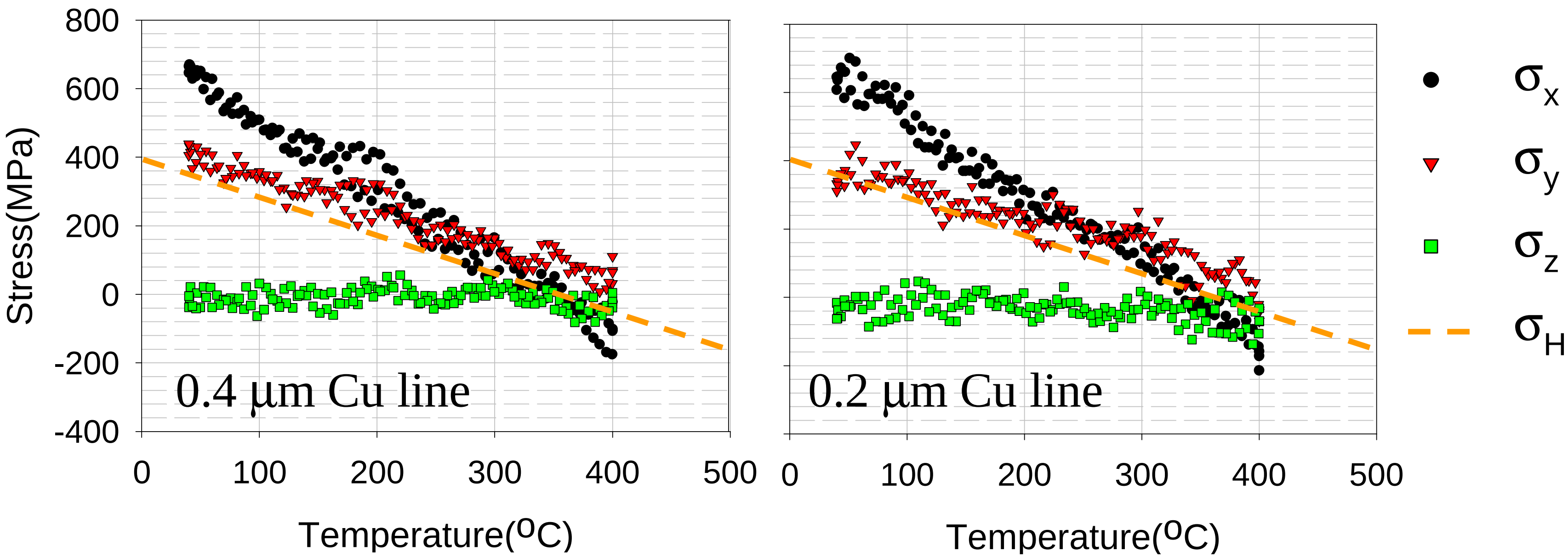
2. Stresses in Cu lines (Cu/SiLK™ damascene structure)



- Linear behavior with temperature
- $\sigma_z \sim 0$, smaller σ_x and σ_y at RT
- σ_H--lower than SiOF, weakly dependent on linewidth

Characteristics of thermal stress of Cu lines

3. Stresses in Cu lines (Cu/CDO damascene structures)

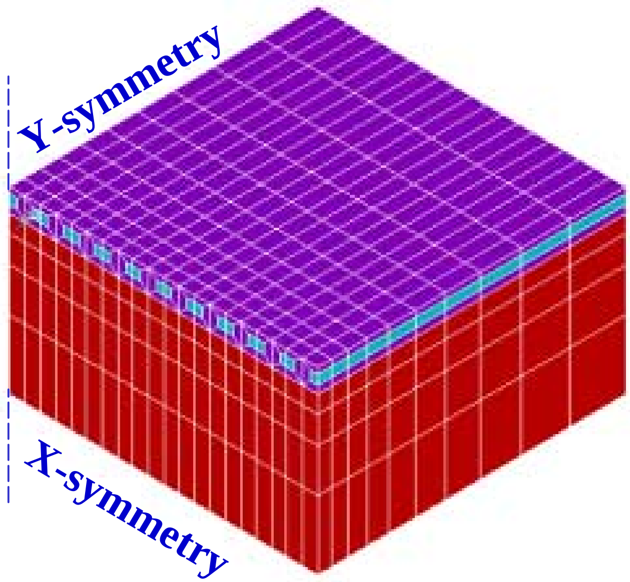


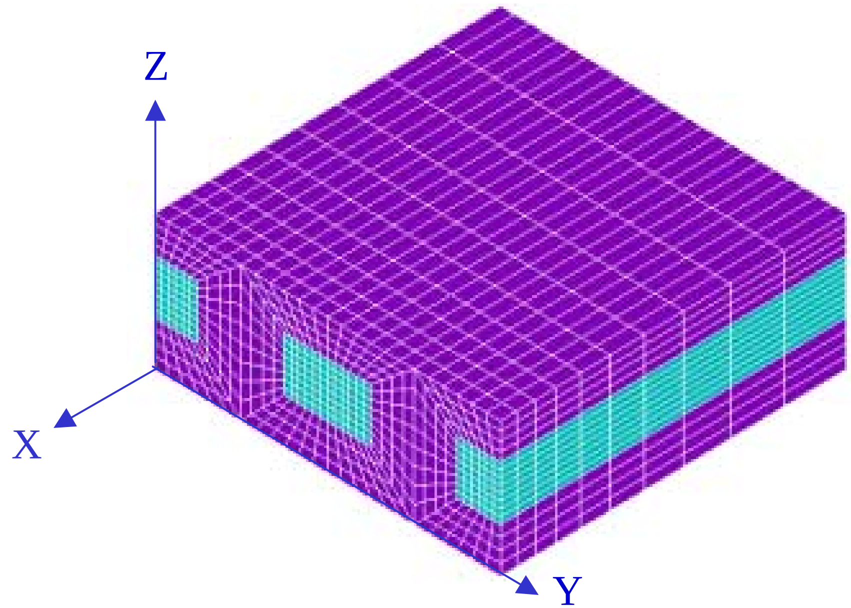
- Linear behavior with temperature
- σ_z ~ 0, comparable σ_x and σ_y at RT
- σ_H--lower than SiOF, but higher than SiLK™, weakly dependent on linewidth

*** The effect of different low-k ILD on Cu line stresses is not very strong**

3D finite element analysis

Development of models





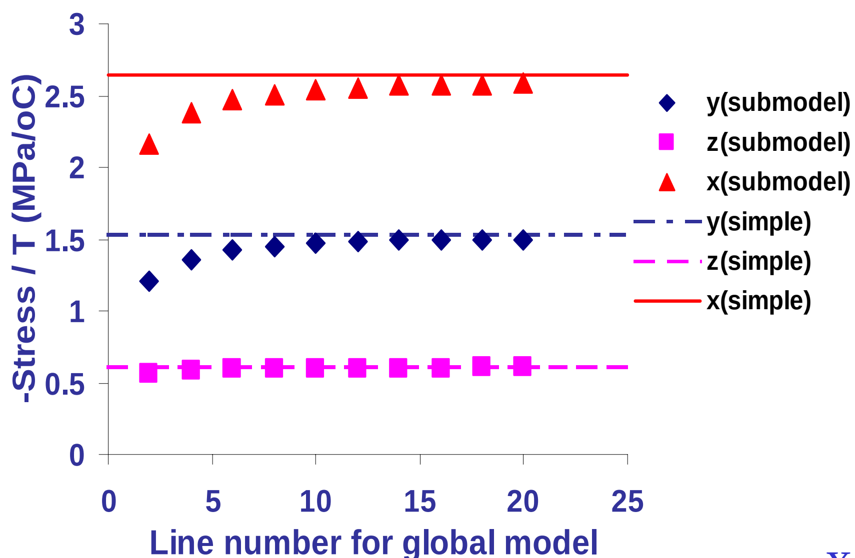
Boundary condition →

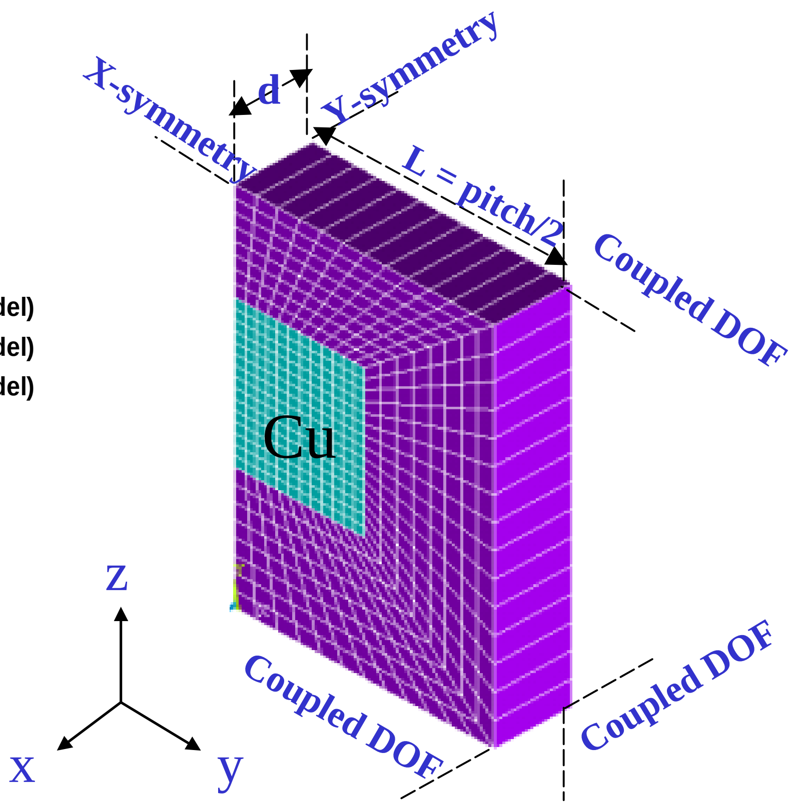
Global Model
- Si: full thickness
- Line number: up to 20

Sub-model
- The substrate confinement is taken into account

3D finite element analysis

Solution convergence verification





- Cu/TEOS structure
- Linear elastic approximation

Simple model

- Contains half pitch

With proper boundary conditions, a simple model can be used to evaluate thermal stress behavior.

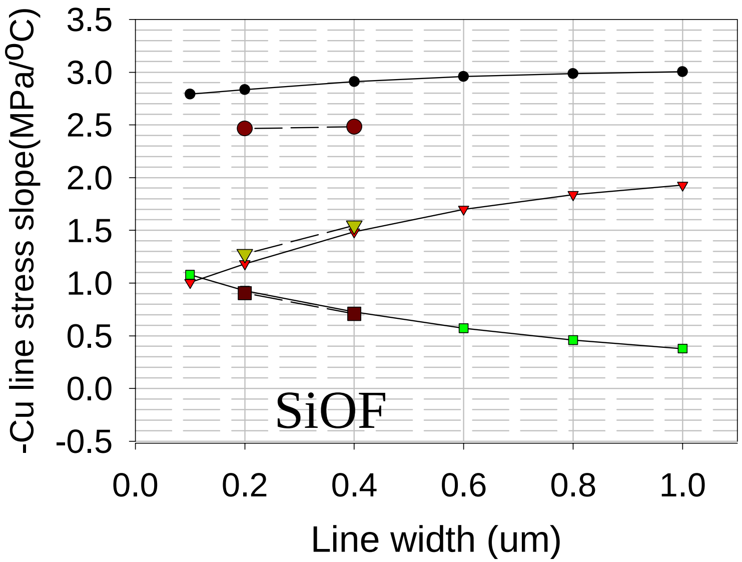
3D finite element analysis

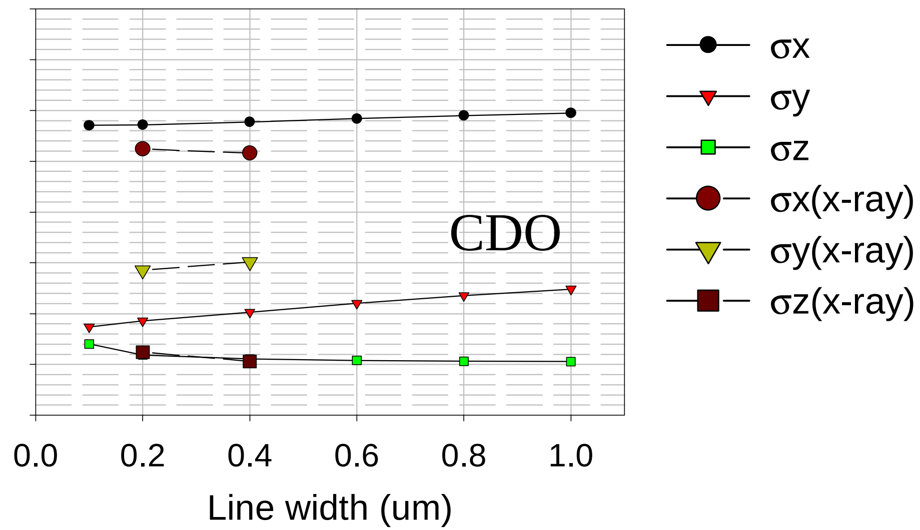
- Diffusion barrier is important and has to be considered
- Linear elastic behavior
- 100 percent of <111> texture in Cu lines
- No delamination at interfaces

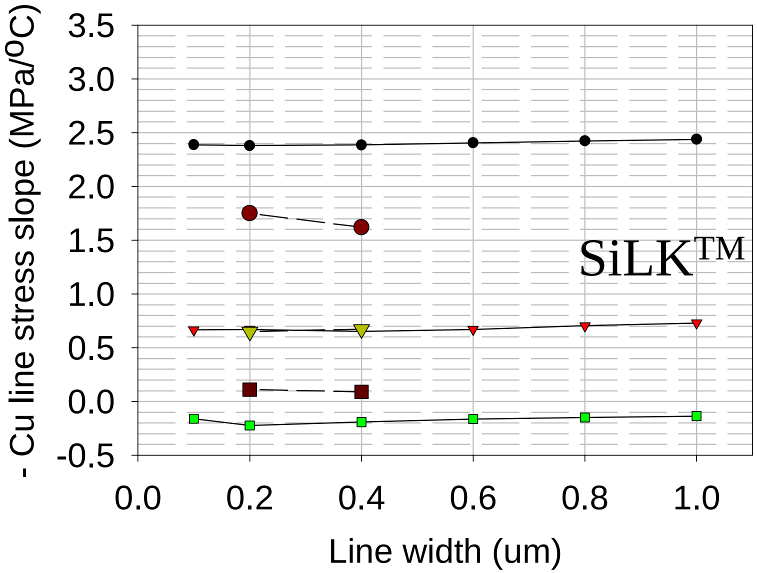
Mechanical properties of the related materials at 25°C

Material	E (GPa)	ν	CTE(ppm/°C)
Copper	$[C]_{<111>}$		17.0
Silicon	130.2	0.28	2.3
SiOF	71.7	0.16	0.94
CDO	4.47	0.30	12.9
SiLK™	2.45	0.35	66.0
Ta	185.0	0.34	6.5

3D finite element analysis

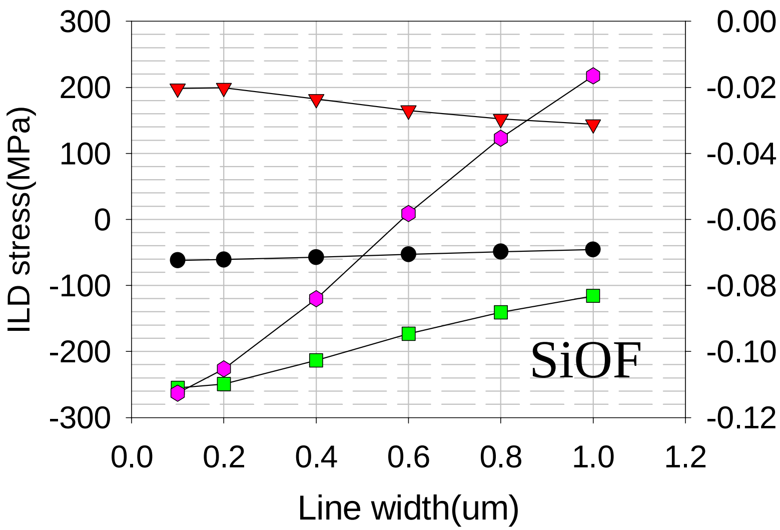


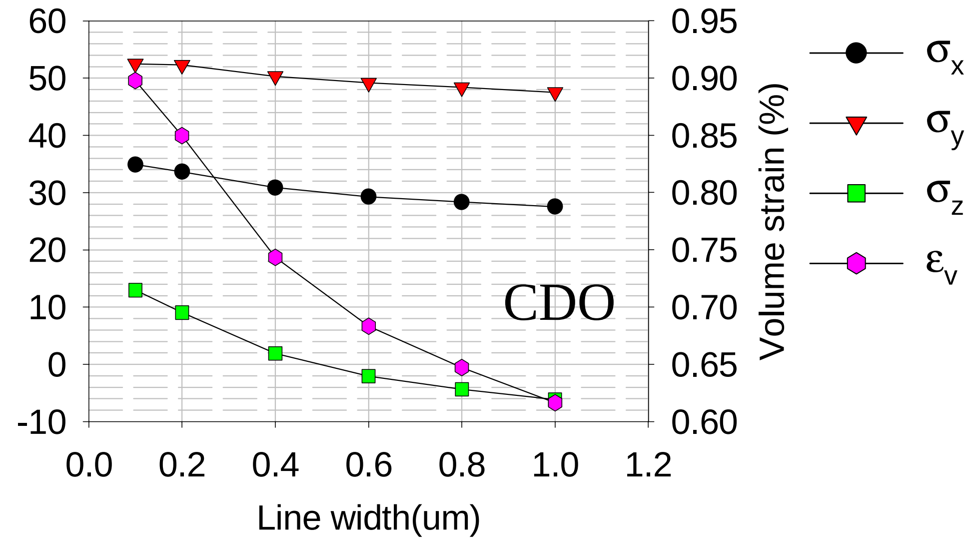


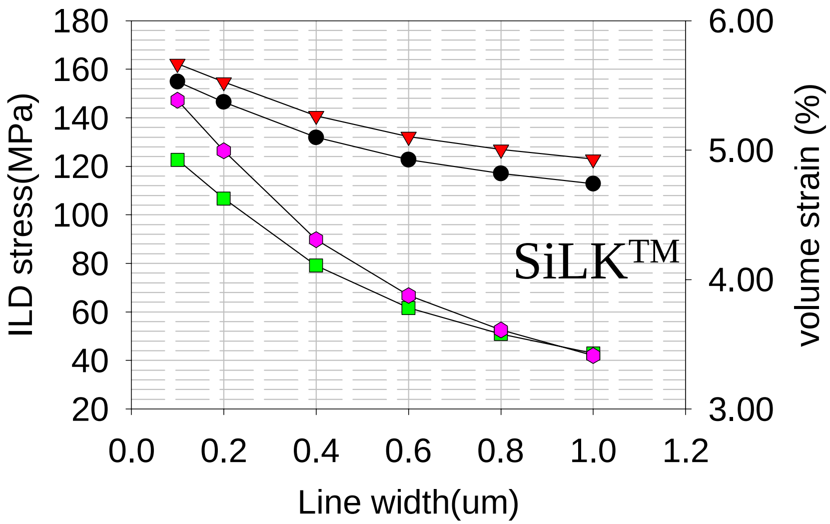


- Stress slopes of Cu are weakly dependent on linewidth for SiLK^{TM} and CDO structures
- Reasonable agreement between FEA and x-ray results

3D finite element analysis







- Similar characteristics (hydrostatic) in SiLK™ and CDO, different in SiOF
- Large volume strains in SiLK™ and CDO, up to 50~100x higher in SiLK™ than in SiOF

Summary

- Thermal Stresses of Cu lines in damascene structures were measured under thermal cycling using x-ray diffraction method.
- The overall stress behavior of Cu lines was found to be weakly dependent on linewidth and properties of ILD, indicating that the barrier and substrate are important in controlling Cu thermal stresses.
- Thermal stress and strain characteristics as a function of linewidth for ILD have been deduced using FEA. Results indicate different behavior for SiOF in comparison with SiLK^{TM} and CDO.
- Thermal strains in SiLK^{TM} and CDO are significantly higher than SiOF. The strain in SiLK^{TM} can reach a level of 3~6% and thermal stresses become more hydrostatic with decreasing linewidth.